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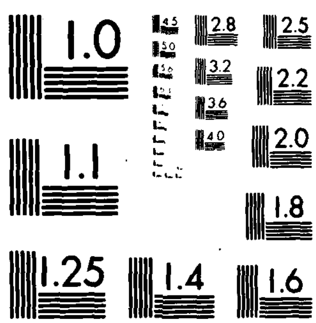

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20. Abstract

Five distinct avenues of research relating to thunderstorm electrification are presented: Airborne Studies of Thunderstorm Electrification details some results of the three-year Thunderstorm Research International Project (TRIP); Charge Transfer Accompanying Collisions Between Hailstones and Supercooled Raindrops in the Presence of an Electric Field; Charge Transfer Accompanying Individual Collisions Between Ice Particles, Surface Potential Steps and Their Role in Thunderstorm Electrification; The Growth of a Positive Streamer System; Laboratory and Theoretical Studies of the Raingush Phenomenon. The last four sections above are summaries of laboratory experiments conducted at the University of Manchester Institute of Science and Technology.

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INTRODUCTION

Five distinct avenues of research relating to thunderstorm electrification have been pursued under Grant No AFOSR-77-3429 and each topic is presented as a distinct section of this report.

Collaborative field studies of thunderstorm electrification, principally in New Mexico have been carried out in conjunction with personnel from New Mexico Institute of Mining and Technology. The primary objective of this work was to establish the electric charges and masses of hydrometeors within the lower regions of developing thunderclouds with a view to elucidating the charging processes responsible.

Laboratory studies conducted at UMIST and reported as sections II and III explored the charge transfers associated with both ice-ice and ice-water particle interactions in conditions likely to be present within natural storms. In addition, investigations were made of the growth mechanisms of positive corona streamers in electric fields.

Finally, laboratory and theroetical work has been performed in order to explore the raingush phenomenon in which a sudden intensification of reflected radar signal is reported to occur, on some occasions, in the vicinity of the channel of a preceding lightning stroke. It is suggested that the stroke charges cloud droplets both directly and indirectly and greatly increases their collection efficiencies resulting in the very rapid development of precipitation-sized particles.

SECTION I

AIRBORNE STUDIES OF THUNDERSTORM ELECTRIFICATION IN NEW MEXICO

In the summer of 1976, 77 and 79 the ONR/NMIMT research aeroplane was employed in studies of the electrical properties of thunderstorms. Flights through clouds were made in New Mexico, as part of the Thunderstorm Research International Project. The most important measurements were of electric field, E, and the charge, Q and size, d, of individual precipitation elements. A novel device was constructed for the Q and d measurements. The charge carried on a particle passing through a metal cylinder was sensed by induction, and its size by a shadowgraph technique involving a linear array of photodiodes. Five rotating-vane field-mills were used to measure all three components of E. The penetrations were generally through the lower regions of the clouds.

The major findings in 1976 were as follows:

1. Volume charge densities on precipitation, ρ_p, were often around $-5Ckm^{-3}$ over horizontal distances of several kilometres, ρ_p was almost always negative, but positive charge densities, of lower magnitude, were occasionally observed over shorter distances. The major contribution to the measured values of ρ_p was made by particles of size around 1 mm, or smaller.

2. Simultaneous measurements of Q and d showed that no simple relationship existed between them. Charges of about 100 pC were commonly observed on particles around 1 mm in size. These are much too high to be explicable in terms of the inductive theory.

3. Positive and negative charges were found to coexist, except when the precipitation rate, p, was very low. However, charge of one sign (almost invariably negative) was always strongly dominant.

4. Values of p could be estimated crudely from the d pulses. In regions of high ρ_p they were rarely in excess of 10 mm h^{-1}; on some occasions when ρ_p was substantial p was below 1 mm h^{-1}.

Flights through the central regions of thunderstorms were made over New Mexico on 6 and 15 August 1977. In addition to the measurements made in 1976 information was also obtained on the earlier day, with: a rain-gauge network surrounding Langmuir Laboratory; a 3 cm radar; an acoustic system for locating lightning channels; a ground-based field-change meter.

The first cell on 6 August produced precipitation at the ground but no lightning. Vertical fields, E_z, of up to about 50 kVm^{-1} and precipitation charge densities ρ_p of up to -0.5 Ckm^{-3} were recorded within the cloud. The second cell, which grew as the first one decayed, produced 7 lightning strokes in 9 minutes during which time the radar revealed vigorous vertical growth in a narrow zone containing precipitation.

Thunder reconstructions showed the acoustic sources for the first flash of this cell to be very near the top of the cloud at an altitude of 10km a.s.l. The subsequent flashes produced acoustic signals from progressively lower in the cloud. When the radar echo reached its maximum height lightning activity ceased. E_z values of up to about 50 kVm^{-1} and ρ_p values of down to $-1Ckm^{-3}$ were measured.

ρ_p was consistently negative, individual charges being less than ±40pC. Q values were within the inductive limit for a thundercloud at breakdown but no systematic relation between Q and d was found.

Six penetrations were made through the thundercloud of 15 August, which produced only two lightning strokes. The E_z records were indicative of a (±) dipole located near the cloud top, at around -13^oC. Fields of up to about 100 kVm^{-1} and ρ_P values (positive and negative) of around 5 Ckm^{-3} were measured. Q values of up to ±250pC were recorded, with charges around ±50pC being commonly found. No systematic Q/d relation was revealed, and smaller precipitation particles frequently carried charges (positive or negative) in excess of the inductive limit, as shown in Figure 1.

On both days estimated precipitation rates were of order 10 mmh^{-1} and on most occasions the pilot reported precipitation particles to be either 'ice' or 'mixed liquid water and ice'.

Our primary conclusions are that in the clouds studied substantial currents were often carried on precipitation, and that the charges on individual precipitation elements are not explicable in terms of the inductive mechanism of thunderstorm electrification.

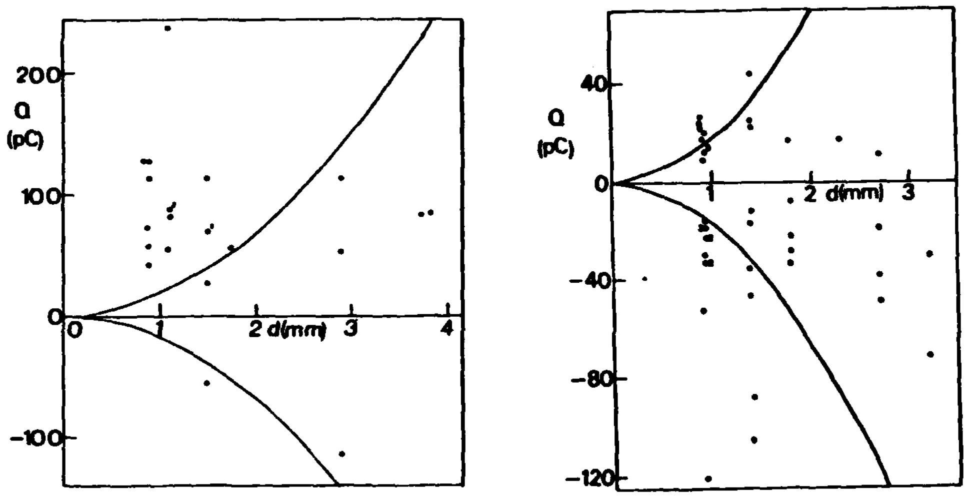

Figure 1. Charge-size (Q/d) coincidences measured in the 65 seconds of successive penetrations on 15 August 1977. The solid lines are theoretical maxima for the inductive mechanism operating in a breakdown field ±300 kVm^{-1}. The numbers attached to certain points are the numbers of observations at those points.

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Gaskell, W., Illingworth A.J., Latham, J. and Moore C.B. 1978 Airborne studies of electric fields and the charge and size of precipitation elements in thunderstorms, Quart.J. R. Met. Soc., 104, 447-460

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SECTION II

CHARGE TRANSFER ACCOMPANYING COLLISIONS BETWEEN HAILSTONES AND SUPERCOOLED RAINDROPS IN THE PRESENCE OF AN ELECTRIC FIELD

1. INTRODUCTION

In this paper we describe experiments designed to examine the influence of impressed electric fields upon the charge transfer accompanying collisions between supercooled water drops and artificially produced hailstones. They were performed with the same apparatus and covered the same range of conditions as were employed in the field-free experiments of Latham and Warwicker (1980). Thus we present herein only a skeletal account of the experimental arrangement and procedures.

Latham and Warwicker found that the charge Q acquired by the hailstone during a splashing event was positive and of order 30 fC over the entire range of conditions covered by the experiments: temperature T_a of air and of hailstone, 0 to -20°C; impact velocity U, 1 to 4 m s^{-1}; impact parameter 0 to ± 1; drops of differing chemical constitution; and hailstones of various shapes and surface structure. This value of Q - which agrees with ones obtained in similar experiments by Crabb (1973) - is far too small to be of major importance in thunderstorm electrification. However, in common with several other processes involving the collision and separation of hydrometeors in thunderstorms, it seemed possible that in the presence of electric fields the charge transfer may be much greater.

2. LABORATORY EXPERIMENTS

The apparatus, illustrated in Figure (1), was located within a cold room whose temperature could be varied from 0 to -20°C. A supercooled drop (of diameter 2.3 ± 0.3mm) suspended in the divergent nitrogen stream of a wind-tunnel (Crabb and Latham, 1974) was ejected vertically upwards by means of a pressure pulse, its charge q was limited by passage through an earthed wire, and q and its velocity U were measured before it collided with an ice-coated bronze sphere of diameter 6.4mm. The charge Q conveyed to the hailstone as a consequence of the splashing event was measured, and stereoscopic photography used to study the separation of splash fragments and to determine the impact parameter γ (defined as the ratio of the horizontal distance between the drop trajectory and the centre of the hailstone, to the radius of the latter).

An electric field E was created by applying equal and opposite voltages V to a pair of ring electrodes straddling the hailstone. as illustrated in Figure (1). E could be varied from 70 to 1300 V m^{-1}. Numerical solutions of Laplace's equation, together with other calculations, indicated that the uncertainty in E was about 20%.

Full details of the large number of subsidiary tests and developments performed in order to optimise the experiments, to ensure the reliability of the measurements and to estimate their accuracy have been given by Warwicker (1978) and Latham and Warwicker (1980).

3. RESULTS

The ratio Q/V was found to be independent of the absolute value of V. It follows that the field was insufficient to affect the mechanics of the splash, and that there was no discharge effect between the target and the drop just after separation.

In all experiments the upper ring was at positive potential relative to earth. Thus the inductive mechanism would cause the target to acquire negative charge if the splashing occurred from the underside of the hailstone and positive if from the top side. In almost all circumstances Q was found to be positive, and photographs (Figure 2) confirmed that the splashing drops generally pulled out quite a long filament (up to about 3mm) as they departed from the upper surface of the hailstone. This would induce a substantially greater charge, and is consistent with the observation that when negative values of Q occurred they were much smaller than the positive ones; there is no mechanism of filament production when splashing occurs from the underside. We note that these positive values of Q are <u>dissipative</u> of the existing electric field. Because of the linearity of the charge-field relationship, and because it passed through the origin, it was thought unlikely that any significant information could be gained by reversing the field.

The measured relationship between Q/V and impact parameter γ is shown in Figure (3), and that between Q/V and impact velocity U in Figure (4). The general findings were essentially independent of temperature, suface structure of the hailstone and chemical constitution of the drop.

4. DISCUSSION

The dependence of charge on impact parameter can be explained as follows: when the impact is square on, the drop has a small component of velocity parallel to the hailstone surface, so it is likely to stay more or less where it is for the duration of the splash. But in a more glancing impact, the drop, having a larger parallel component of velocity, is more likely to move round the target. From the graph of charge against impact parameter, it can be seen that nearly all the drops arriving at more than the threshold value of impact parameter show substantial charges transferred, indicating that the departing drop extends the electrical length of the hailstone quite appreciably.

The tendency, revealed in Figure (4), for Q/V to increase with U is possibly a consequence of the fact that at higher velocities there is a greater chance of sufficient momentum being available for the drop to swing round to the top of the hailstone before separation occurs.

In both impact parameter and velocity dependencies, the charge per unit field is roughly constant above the threshold. This is probably because there is a maximum length of filament, which would be only a slow function of departing drop velocity.

The experiments showed that in an applied field of magnitude $E = 100V\ m^{-1}$ the charge acquired by the ice target as a consequence of a splashing event was in the region of 40fC. This exceeds the values of charge measured in the field-free experiments of Crabb and Latham and Warwicker. It follows that any natural (non-inductive) charge separation between supercooled raindrops and hailstones over the range of conditions covered will be masked by induction, except at very low fields, and thus will constitute a negligible effect in terms of thundercloud electrification.

It is also apparent that the splashing collisions of supercooled drops with raindrops in the presence of electric fields cannot be responsible for electric field growth in thunderstorms, since the experiments showed that the dominant effect is <u>dissipative</u> of the electric field - splash fragments leaving from the topside of the hailstones. Simple calculations (based on the model of Illingworth and Latham (1977)) of the extent to which this process may inhibit field-growth show that even with the optimum apportionment of precipitation between water and ice the dissipative effect would be important only for precipitation rates of order $100mm\ hr^{-1}$. Thus we conclude that raindrop/hailstone splashing events will never assist field growth, and only in exceptional circumstances may significantly impede it.

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J A Crabb & J Latham	1974	Q J Roy Met Soc, <u>100</u>, 191-202
A J Illingworth & J Latham	1977	Q J Roy Met Soc, <u>103</u>, 281-295
J Latham & R Warwicker	1980	
R Warwicker	1978	Ph D Thesis (Manchester)

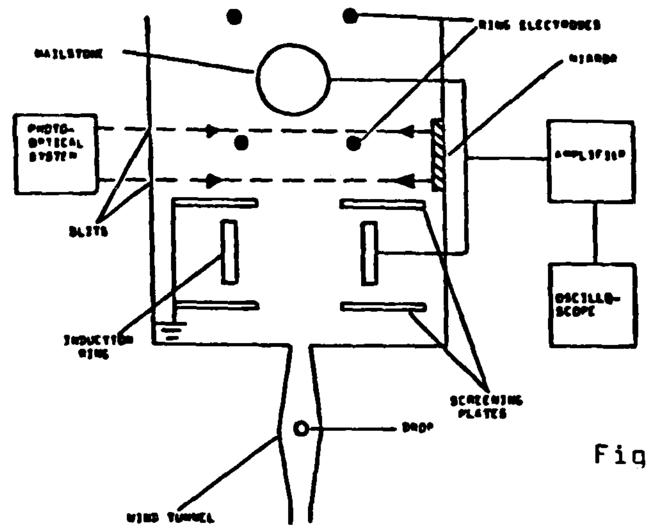


Figure II.1:The experimental Arrangement.

Figure II.2: Splash water pulling away from the upper surface of a rimed hailstone, about 5ms after collision, $V=1.5 m\ s^{-1}$; $T=-12^{o}C$.

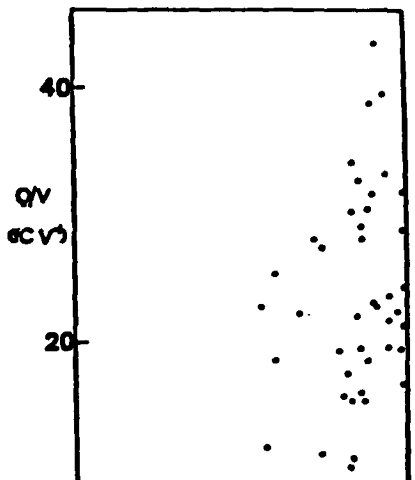


Figure II.3: The measured variation of Q/V with impact parameter Υ. 10^{-4}M NaCl; $T=-8^{o}C$; $V=1.5 m\ s^{-1}$.

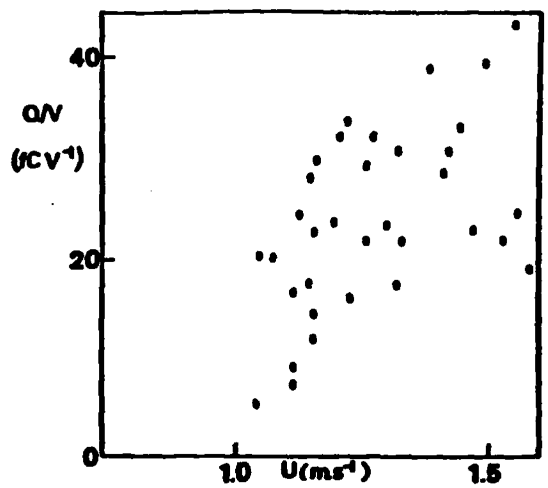


Figure II.4: The measured variation of Q/V with impact parameter U. 10^{-4}M NaCl; T+-12^{o}C.

SECTION III

CHARGE TRANSFER ACCOMPANYING INDIVIDUAL COLLISIONS BETWEEN ICE PARTICLES, SURFACE POTENTIAL STEPS AND THEIR ROLE IN THUNDERSTORM ELECTRIFICATION

Experiments have been conducted with a wind-tunnel in a cold-room in order to investigate the individual charges transferred when ice spheres collide with an artificial hailstone.[1,2] The charge transferred to a sublimating hailstone was negative and had a magnitude proportional to the velocity of impact (Fig. 1A) and to the diameter of the ice spheres to the power of 1.7. (Fig. 1B). Each point in these figures represent the average valve from about 100 collisions, the individual charges showing considerable scatter. The charge transferred when a 100μm diameter ice spheres collided with the hailstone at a velocity of 8m s^{-1} was typically -15fC. No variation of charging could be detected over the temperature range -5°C to -25°C when the ice was doped with impurities, or when hailstones of different surface roughness were prepared.

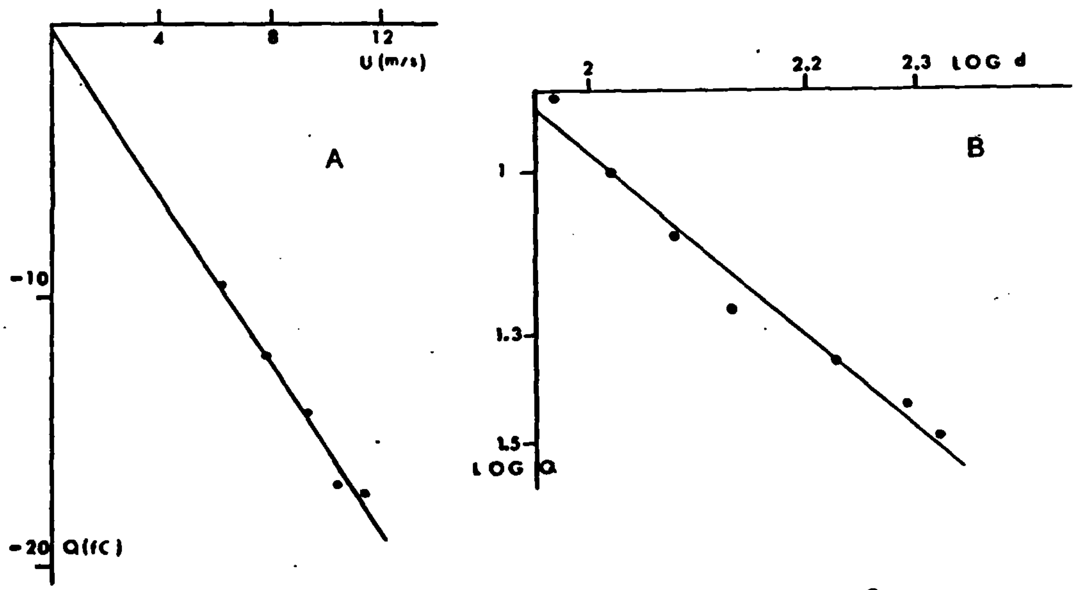
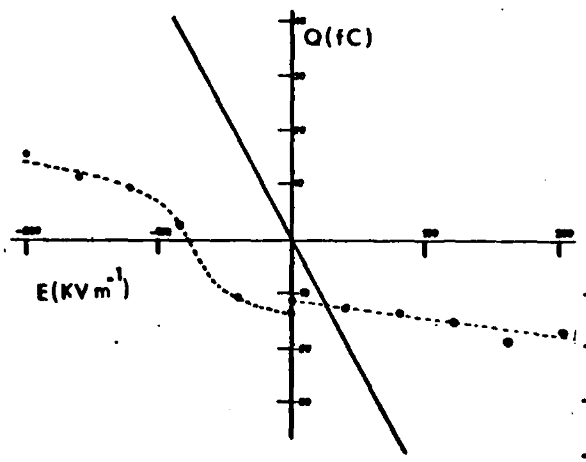


Figure III.1 The charge transferred to a hailstone at -10°C by a small ice sphere, (A) as a function of velocity, U, for a 100μm sphere, (B) as a function of sphere size, d, (U = 8 ms^{-1})

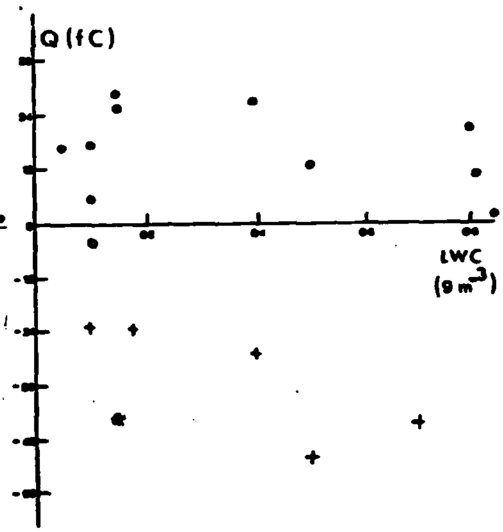
The charge transfer as a function of a radial external electric field is shown in Figure 2 and can be seen to be much less than that predicted by the inductive mechanism.

Similar behaviour was found over the range -5°C to -25°C. If the inductive mechanism were responsible for the charge transfer but was being limited by the ice conductivity, then a large difference in charging with temperature would have been expected as the conductivity changed.

Hailstones which were cooled below the ambient cold-room temperature and subsequently grew by deposition, charged positively by typically 100fC/collision. However, a hailstone which was cooled by the same amount but was maintained in a sublimating condition charged negatively. These experiments show that thermal effects did not play a direct role in the charge transfer process. Experiments were performed with a riming hailstone in order to simulate the conditions found in a natural cloud. The hailstone charged positively at temperatures of -5°C and -10°C and negatively at -15°C and -20°C with liquid water contents in the range 0.05g m^{-3} to 0.85g m^{-3}, the magnitudes of the charges being typically 30fC, as shown in Figure 3.



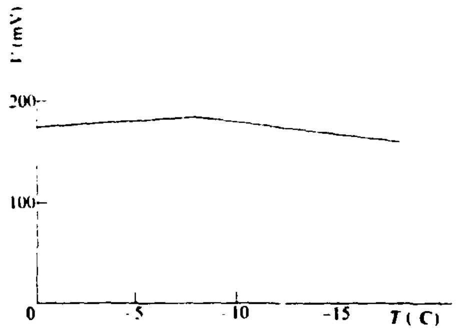
III.2 Charge transferred to the hailstone against field, the straight line is the inductive theory prediction.
(d = 100μm, U = $8ms^{-1}$, T = -10°C)



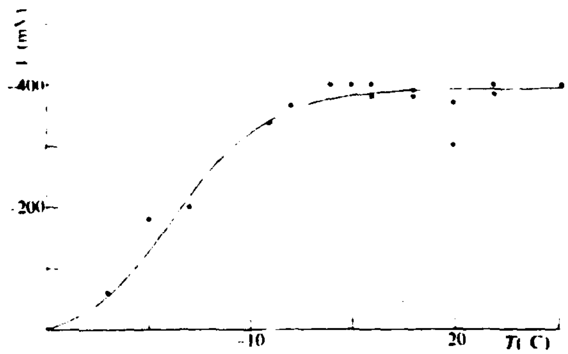
III.3 The charge transferred to the hailstone against liquid water content for four different temperatures.
● -5°C, O -10°C, + -15°C. * -20°C.
(d = 100μm, U = $8ms^{-1}$)

Because the charge transfer varied with ice sphere size and velocity in the same manner as the predicted contact area (Hertzian theory) it seems possible that the charge transfer occurs from one ice surface to the other at the contact interface, thus avoiding any relaxation time problems, and that the driving force for the charge transfer at the contact interfaces is the different surface potentials and/or different charge carrier densities of ice surfaces formed in different ways. Buser and Aufdermauer[3] have suggested that the work function difference between evaporating and condensing ice reported by Takahashi[4] might be responsible. To check this idea changes in the surface potentials of polycrystalline ice during evaporation, condensation and following riming with supercooled water droplets were measured using the Kelvin vibrating capacitor technique.[5] During evaporation and condensation only small changes in potential of between 1 and 2mV/°C could be detected (Figure 4). The ice specimen was attached to a lower noble metal electrode and kept at constant temperature whilst the air temperature was varied. No sudden step in potential as the ice surface changed from an evaporating to a growing state could be identified. The other noble metal electrode was kept 1°C warmer than the lower one to prevent frost forming upon it. Frost formation on the upper electrode resulted in large spurious potential changes similar to those

The most striking changes in surface potential were observed when the ice surface was rimed with supercooled water droplets from an ultrasonic generator. The ice surface, air, and supercooled droplets were all isothermal. The change in potential was a function of the supercooling of the water droplets, and increased from zero at 0°C to about -400mV at -15°C and remained at that level down to at least -25°C (Figure 5). The changes persisted for several hours, but could be reversed by melting the rimed surface and allowing it to refreeze slowly showing that the potential jump occurs at the surface. The effect of impurities was small, although during the actual rapid freezing of the droplets large transient Workman-Reynolds freezing potentials were produced.



III.4 Variation of the surface potential, V, (arbitrary zero), of ice using gold electrodes with air temperature T. In this example the ice is at -8°C.



III.5 Change in the potential step at the surface, V, of ice after riming as a function of temperature T. The unrimed ice surface is assigned a potential of 0V.

It is suggested that the difference in the potential step at the surface of up to 400mV existing between colliding vapour grown ice crystals and rimed hailstones may be the driving force which results in charge separation within thunderstorms. It is possible that the charge carriers may be ions of a liquid like layer[8] on the surface of the ice, which are present in sufficiently high numbers at the contact interface. The rapid freezing of rime at low temperatures may result in a more disordered structure which allows a change in surface dipole orientation. The proposed charge transfer process for an initially uncharged hailstone and a vapour grown ice crystal having different potential steps at their surfaces is depicted in Figure 6.

The temperature dependence of the charging shown in Figure 3 is similar to the riming results of Takahashi[7], and can be explained in terms of Figure 5, if the rime formed at 0°C is arbitrarily assigned a surface potential step of 0V, the small ice sphere or crystal -200mV, and the rime formed at -25°C a value of -400mV.

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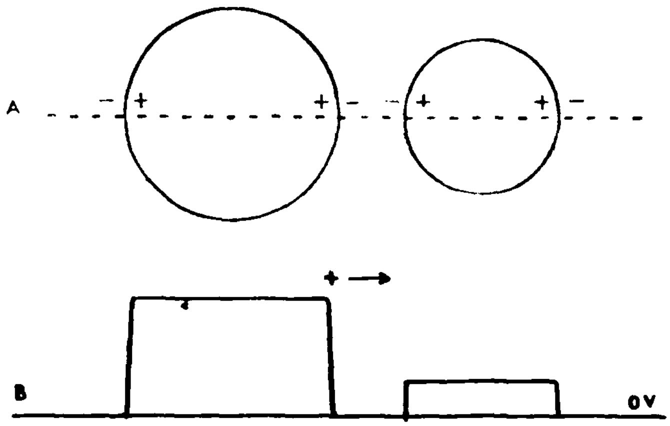

III.6 A. Differing dipole layers on the surface of two uncharged ice spheres. B. The potential variation along the dotted line in Figure A. The arrow shows the direction of charge flow when the spheres touch.

[illegible] ... C.T. Phelps (1974) has suggested an exponential growth of charge from total luminosity measurements in a gap of 50 cm whilst the theoretical model of Griffiths and Phelps (1976), which takes into account the electrostatic energy of the separated charge, predicts an x^2 growth for distances greater than $\sim$ 1 m. The results reported briefly here were obtained in a 13 cm gap using the Lichtenberg figure technique; this is the only approach which allows a study of individual streamer tips, the behaviour of which must govern the growth of the system as a whole. A weaker growth has been observed.

EXPERIMENTAL

Corona streamers were produced from a point electrode located at the centre of a small hole in the earthed plate of a uniform field assembly; the single square voltage pulse used to produce corona is 100 ns long and has an amplitude V_p continuously variable upto 25 kV. Without any ambient field E_A the range of the streamers was $\lesssim$ 1 cm. Lichtenberg figures were obtained in two ways; either with the plane of the photographic film in the same direction as E_A or transverse to it; only results from the transverse Lichtenberg figs. (TLF) are discussed here. The TLF's yield estimates of the total number of branches or tips, tip potential and number densities. Placing the film at different positions thus gives an indication of the variation of these parameters with E_A, V_p and x, the distance from the streamer source. Although the entire electrode assembly is contained within a chamber designed for variations in gas pressure and composition, all the measurements reported were obtained in room air at atmospheric pressure. A typical TLF is shown in Fig.1.

RESULTS

For each of the parameters E_A, V_p and x, 3 TLF's were analysed and an average taken; V_p was set at either 5 or 15 kV.

a) Growth of tip numbers n(x)

A sample of these measurements is shown in Fig. 2. For V_p = 5kV the growth in n depends upon E_A and varies from almost zero for E_A = 4.36kV cm^{-1} to 12 cm^{-1} for E_A = 7.22 kV/cm; in the absence of the film the gap would normally breakdown at this field. For V_p = 15kV an initially high value for dn/dx falls away in midgap and, for the higher fields, increases again in the second half of the gap. For the highest ambient field of 6.47 kV cm^{-1}, dn/dx $\sim$ 15 cm^{-1} for the entire gap. These variations can be explained in a qualitative way in terms of the behaviour of the average streamer tip potential. Although the gap is small and the measurements subject to the inherent statistical variations common to all corona work, there is no evidence [illegible]

b) Tip Potential V_T

Nasser and Loeb (1962) have demonstrated that the maximum range of the streamers emerging from an impact point on a TLF is proportional to the tip potential; after impact the streamers are diverted along the plane of the film and so move in an effectively zero ambient field. Of course, not all streamer tips have the same potential; a given tip is a product of its history and represents the nett effect of a number of branching events, which lower the tip potential and growth in the ambient field which raises it. An example of the way the tip potential distribution changes as the propagation proceeds is shown in Fig. 3. The important feature is the tendency for the distribution to achieve an equilibrium value which itself depends upon the strength of the ambient field E_A. A more striking illustration of the developing equilibrium between the streamer system and the ambient field is shown in Fig.4 where average tip potential V_T is plotted against x for different values of V_p and E_A. The systems initiated at a V_p of 5kV evidently have a value of V_T below the equilibrium value corresponding to all the applied ambient fields and this leads to an initial increase in V_T. By contrast, the 15kV streamer systems have an initial V_T which is too low for the high ambient fields and vice-versa leading to an increase or decrease in V_T respectively. The equilibrium value of V_T is independent of V_p and proportional to E_A; a result which conflicts with the theoretical model developed by Phelps (1974) who assumes V_T is independent of E_A.

Streamer Number Density σ_s

For a given TLF the measured area occupied by a known number of streamers yield σ_s. For those ambient fields likely to give rise to significant growth values of σ_s are found to be $\sim 2\ cm^{-2}$. If the average charge on a streamer tip is q then, upon branching, the repulsive field E_z which separates the product streamers is $\propto q/Z^2$ where Z is their separation. Thus if $q \propto V_T \propto E_A$ and all streamers achieve ultimately the same E_A/E_Z ratio then the final separation Z_o and therefore σ_s should be constant and independent of the range.

DISCUSSION

The effect of the constant growth rate, average tip potential and number density leads essentially to a much lower charge in the head of a growing system than that predicted previously. After 1km. the charge separated is only $\sim 3 \times 10^{-4}$ C. Although the system is initiated in a time of 100ns, evidence from point-plane work suggests that longer pulses ~ 1 ms (i.e. a factor of 10^4 longer) only produce an order of magnitude more streamers; the growth rate would, in any case, be expected to depend finally upon the ambient field rather than the initial conditions.

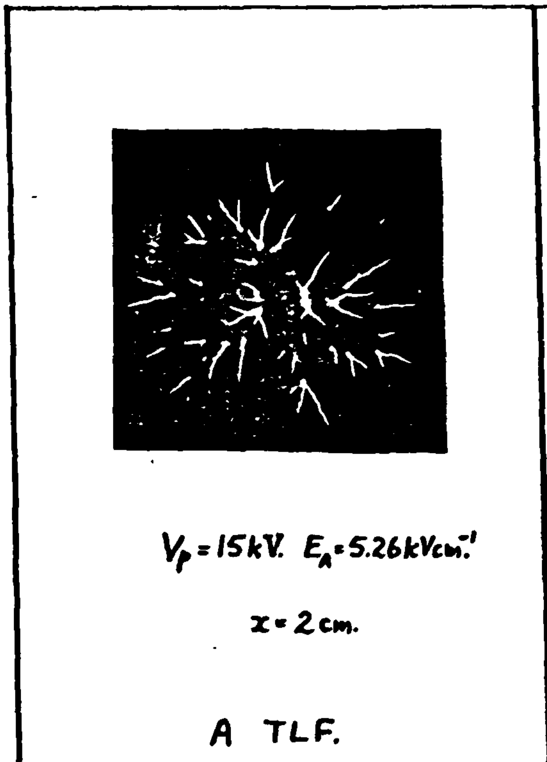

Figure IV.1

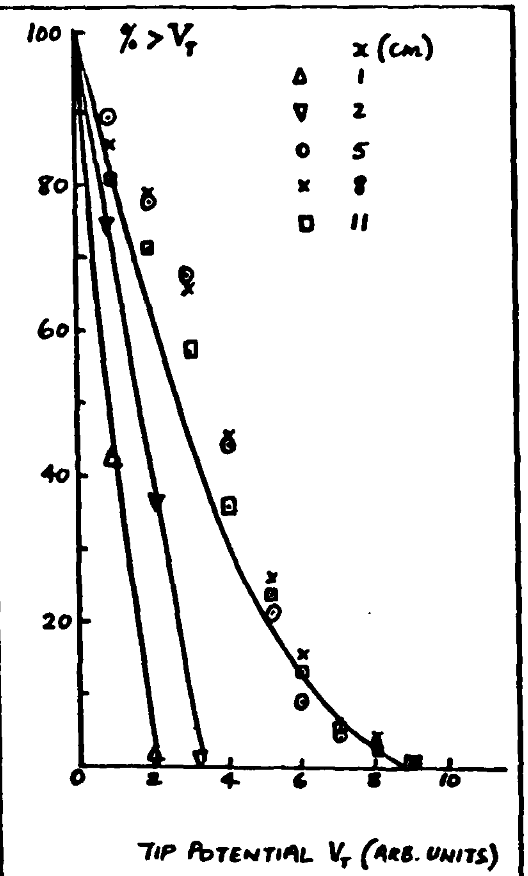

Figure IV.3

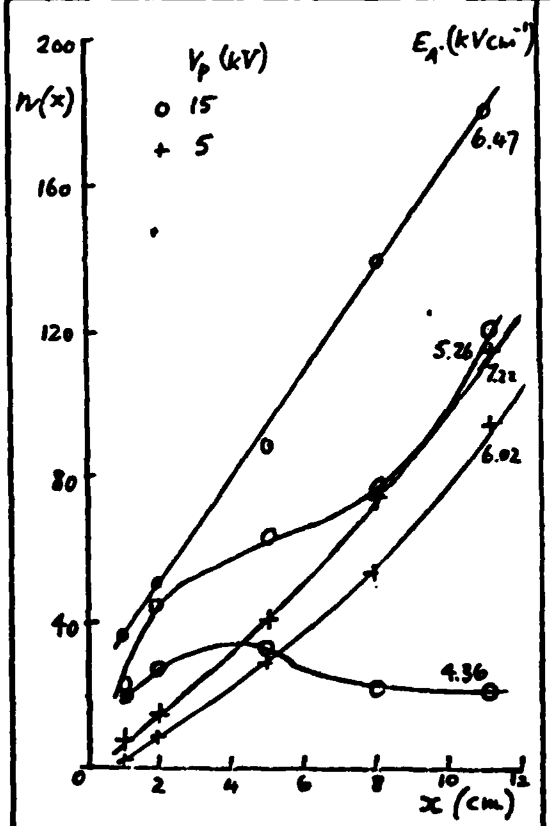

Figure IV.2

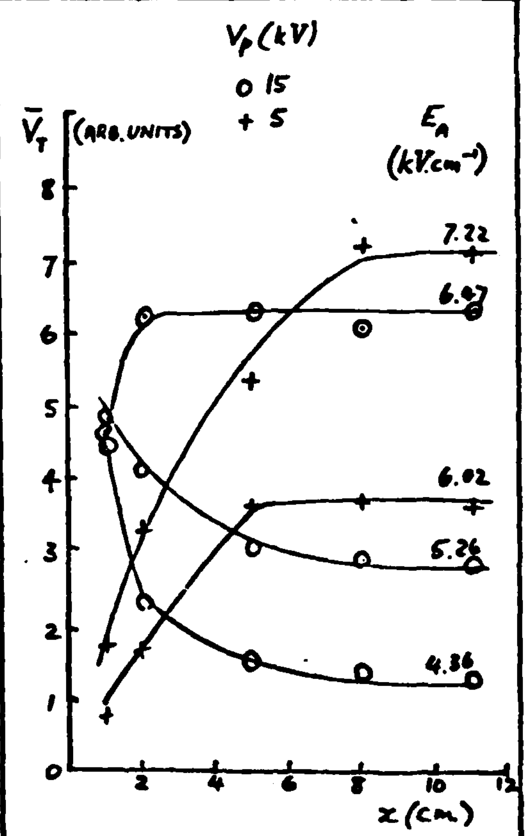

Figure IV.4

SECTION V

LABORATORY AND THEORETICAL STUDIES OF THE RAINGUSH PHENOMENON

Moore, Vonnegut and collaborators have reported in several papers describing their radar studies of thunderclouds, that following a lightning stroke a sudden intensification of reflected signal sometimes occurs in the vicinity of the channel. They attribute this to the rapid formation of rain resulting from increased collection rates of droplets highly charged by interaction with corona streamers. Laboratory and theoretical studies have been performed in an effort to explore in more detail aspects of this phenomenon.

THE LABORATORY MEASUREMENTS.

(1) Measurement of charges deposited on drops following direct interaction with positive streamers

The charges deposited on water drops following a direct interaction with a positive streamer were measured for drops having radii in the range 12 - 950μ using three separate techniques for drop production namely the spinning top (12-30μ), the Abbott and Cannon drop generator (35-85μ) and the Atkinson and Miller drop generator (200-950μ). Following production the cloud or shower of drops was allowed to fall freely through vertical parallel electrodes. A 30kV high voltage pulse of duration 1ms. applied to a point electrode protuding through a PTFE stud in the HV electrode, produced positive corma streamers: the same pulse was used to establish between the plain electrodes the ambient field in which the streamers propagate. Variations in this ambient field were achieved simply by moving the earthed electrode; in all cases the minimum field used was sufficient for the streamers to cross the gap. The charge deposited on the small drops was measured using a charge amplifier connected to the earthed electrode and a sweeping field derived from a voltage pulse of 8ms duration which was applied immediately after the termination of the 1ms HV pulse; the polarity of this field was such that the positive drops were swept towards the earthed electrode and the negative debris in the opposite direction. The larger drops were allowed to fall into a Faraday cup and the charge measured using an electrometer. For the latter case, the rate of drop production was chosen so that only one drop was present in the vicinity of the streamer system during each discharge. In all cases the measured initial charges on the drops were much less ($\lesssim 10^{-16}$C) than the deposited charge ($10^{-13} - 10^{-10}$C). This deposited charge appears to correlate with the n th power of the radius where $1.5<n<2.0$.

(2) <u>The collection efficiency of highly charged drops</u>.

A stream of uniform charged collector drops was generated by a Cannon and Abbott drop generator. Drop radii (between 120μm and 40μm) were measured by impaction on a magnesium oxide coated slide and their charge (0.6 or 3 pC) was measured by the current to an electrometer sampling electrode placed in their path.

The drop stream was injected into a horizontal wind tunnel containing a mono-disperse cloud of droplets of mean radius 12μm generated by a spinning top device. After passing through the cloud the collector drops were recovered and washed into a sample bottle. The collector drops were doped with Co^{++} ions and the cloud droplets with Mn^{++} ions. The ratio of concentrations of the two doping chemicals, measured after recovery, provides a value for the collection efficiency. The concentrations were measured with an atomic absorption spectrometer capable of detecting 2 parts per 10[illegible] in the washing solution.

Efforts were made to ensure that only the collector drops were recovered without contamination of the recovery vessel by cloud droplets which had not been captured by a collector drop, and an estimate was made of the residual contamination which could not be eliminated.

DISCUSSION Charging mechanisms

A streamer system can charge the cloud drops by two distinct mechanisms. It is possible for a direct encounter to occur between a streamer tip and a cloud particle, resulting in a relatively large positive charge being deposited on the particle. The role of these directly charged drops has been considered unimportant because of the small numbers of drops involved and because the mechanism was thought to operate only for droplets above 50μm in radius, (Phelps (1972)) while Sartor (1970) considered the charges deposited on smaller droplets to be more influential in the rapid formation of rain. We have found evidence that direct charging can occur for droplets down to 30μm in radius.

Drops become indirectly charged by the diffusion of ionic debris in the wake of the positive streamers onto nearby cloud particles. This process operates on particles of any size and can produce charges of either polarity depending on whether the system is growing or dying. The size of the charge produced depends on the local electric field existing at the time but has been found to be about an order of magnitude lower than the charges produced by direct interactions, Phelps (1970).

It is the purpose of the present paper to explore the role of directly charged drops in the raingush process, which may have been underestimated by previous workers.

DISCUSSION. Modes of growth

A highly charged cloud drop may grow rapidly either because it acquires a high velocity in the existing electric field, or, when the velocity is low and dominated by gravitational forces, the drop can exhibit high collection efficiency values. Moore and Vonnegut (1964) considered the high velocity mode of growth to be of major importance. However, a simplified calculation (assuming unity collection efficiency and neglecting the radii and velocity of the collected droplets) yields the result that the radial rate of growth per unit path length for all drop radii is $dr/dl = L/4\mu m\ m^{-1}$ where L ($g.m^{-3}$) is the cloud liquid water content.

This implies that drops would have to travel hundreds of metres at high speeds before a significant growth could be achieved; it is unlikely that high electric fields will persist over such long distances after a lightning stroke.

The enhanced values of collection efficiency resulting from high drop charge have been studied theoretically and experimentally by many workers, but the parameter values chosen in their work have not been applicable to the present problem. Our own experimental investigation, while sufficient in scope, suggests that while the collection efficiency of indirectly charged drops is unlikely to rise much above unity, values in the range 1 to 3 may apply for those drops charged by direct interactions.

DISCUSSION. Coulomb and Dipole forces

The enhanced growth rate of a highly charged drop is terminated by neutralisation by cloud droplets of the opposite polarity. The interactions between the drop and a nearby cloud droplet consists of a coulomb component F_c due to the two charges Q and q and a dipole component F_D which results from the charges induced by Q in the smaller drop. The dipole force is short range and acts on all cloud droplets. The coulomb force has a longer range and, if it is an important component in the interaction, will tend to attract selectively the very particles which lead to a rapid neutralisation of the collector while reducing the collection efficiency for cloud droplets of the same polarity.

In general, if the collection efficiency is found to be low it can be concluded that dipole forces played a dominant role throughout the collection process. However the maximum collection efficiency for which this is true depends on the value of Q and q. Following the method of Smith (1976) and using the values of Q found in our experiment for direct charging the values found by Phelps and Vonnegut (1970) for indirect charging and the values of q found by Takahashi (1973), we have concluded that in the case of indirectly charged drops coulomb forces play a dominant role in the initial stages of the collection process. In contrast the greater value of Q on directly charged drops leads to a greater range of conditions in which dipole effects dominate those due to coulomb forces. It follows that a drop charged by direct collision can capture many unaffected cloud droplets without inhibiting its ability to capture more, and thus substantial growth is possible, whereas an indirectly charged drop becomes neutralised more rapidly.

A MODEL OF THE RAINGUSH. Estimation of the numbers of droplets involved.

Using the methods of Griffiths and Phelps (1976) to construct a model of a streamer system developing in a cloud we have estimated the numbers of drops charged as a result of collisions with streamer tips and the charge densities resulting from ion deposition in the streamer trails.

The charge carried by the system of streamer tips is calculated by constructing the energy balance for the system in the ambient field. The total charge deposited in the wake of the streamers is then calculated from the charge conservation equation, while the deposition of charge in direct interactions is calculated from an estimate of the collision cross section between streamer tips (which are assumed to have a radius of 50μm) and drops, together with our own results of the magnitude of the charge deposited in such an interaction. The energy balance equation is not sensitive to the physical process by means of which charge is deposited in the wake of the streamer trails. Hence the effect of charges deposited on droplets or left in the trail as ions is the same. This enables us to calculate the charge density of the ions in the trails.

The results show that a little under 1% of drops collide with streamer tips. Ionic charge densities are greater and more extensively negative when L is high. It follows from this that, since some neutralisation of the positive, directly charged drops is inevitable when negative ions are deposited in the streamer trails, the total growth potential of the electrified drops is greater in regions of relatively low liquid water content.